# PRODUCTION OF A SLOW, MONOENERGETIC METASTABLE NEON BEAM FOR ATOM DIFFRACTION STUDIES

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#### **Abstract**

We present characterization results from a series of atom-optical elements designed to produce a slow, monochromatic metastable neon atomic beam source. These elements include a two dimensional optical collimator, a Zeeman slower and a hexapole magnetic bender. The beam will be diffracted from various gratings for studies of the van der Waals forces governing atom-surface interactions.

## Introduction

Recent developments in nanofabrication techniques have made available transmission diffraction grating structures with sufficient periodicity to enable diffraction of atomic de Broglie waves. A novel and interesting application of atomic diffraction is the study of the potential between atoms and grating surfaces. At distances shorter than the atomic transition wavelength, this potential has the form of the van der Waals potential  $[1] - C_3/r^3$  where  $C_3$  is a coefficient dependant on electronic states of the projectile and surface atoms, and r is the atom-surface distance. This potential has the effect of reducing the grating slit width, thus affecting the observed diffraction intensities. At larger distances, the force obeys the Casmir potential  $[2] - C_4/r^4$  and it is possible to determine the  $C_4$  coefficient by studying the specular reflection [3] of very slow atoms from various surfaces.

Rare-gas atoms are of particular interest to these studies, as they are chemically inert and do not contaminate surfaces. They have easily accessible optical transitions and this facilitates the use of atom optics [4] to manipulate their motion. C<sub>3</sub> coefficients have been measured for ground state rare-gas atoms [5] and recent work has been directed to transmission and reflection diffraction of excited state metastable atoms [3,6]. They are more polarisable than ground-state atoms and exhibit stronger interactions, which may be beyond the scope of approximations made for ground-state atoms [7].

Of obvious importance to diffraction experiments is the coherence of the atomic beam. To ensure large enough diffraction angles, the beam must also have sufficiently low velocity. It is also advantageous to remove background elements that are a side-product of the metastable production process such as electrons and ultra-violet photons. To these ends, we present preliminary characterization of a series of atom optical elements designed to produce a monoenergetic atomic beam source. These consist of a two-dimensional optical collimator and Zeeman slower to reduce the transverse and longitudinal velocities of the beam respectively and a hexapole magnetic bender to deviate the beam from the UV, electron and ground state component of the beam.

## **Hexapole Magnetic Lens**

The force that an atom with a magnetic moment feels in the presence of a magnetic field gradient is given by:

$$\underline{F} = -g_s \mu_b m_i \nabla \underline{B} \tag{1}$$

where B is the magnetic field strength,  $\mu_b$  is the Bohr magneton,  $g_s$  is the Lande g factor (4/3 for the  ${}^3P_2 \rightarrow {}^3D_3$  cooling transition in neon), and  $m_j$  is the z projection of the total electronic angular momentum. By applying an appropriate magnetic field, this force can be utilised to produce a magnetic lens to manipulate the trajectories of atoms. To create a magnetic lens the magnetic field needs to vary spatially in the radial dimension. For the case of a hexapole arrangement of rare-earth permanent magnet elements (Fig. 1b), the magnetic field will vary quadratically in the radial dimension by the relation

$$B(r) = B_0 (r/r_0)^2 (2)$$

where  $B_0$  is the magnetic field strength at the surface of the magnets,  $r_0$  is the inner radius of the ring.

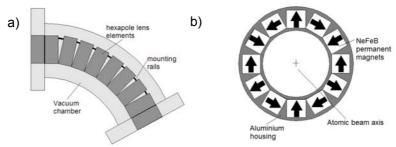


Figure 1 a) Hexapole magnetic bender. The ten magnet elements are mounted on a steel rail to maintain the bend radius. b) The hexapole magnet orientation. The atomic beam travels co-axial to this arrangement.

The gradient of the magnetic field therefore increases linearly with radius and atoms near the edges of the lens, with large transverse velocity, are subjected to a greater force than those on axis. A paramagnetic, weak-field seeking atom will then be harmonically bound to the magnetic axis. Using a "thin lens" approximation, the focal length of the hexapole lens element is given by

$$f = \frac{E_{kin}}{\mu_B \left(\partial^2 B/\partial r^2\right) L} \tag{3}$$

where  $E_{\text{kin}}$  is the kinetic energy of the atoms and L is the length of each element.

If this principle is employed to a series of hexapole magnets placed in the arrangement depicted in Fig. 1a, a magnetic guide can be established whereby the weak-field seeking atoms are attracted by the curved magnetic axis. The radius of curvature of the bender is optimised to transport atoms with a chosen velocity maximum and these atoms can be deflected at an angle of 60° to the undeflected axis.

## 2-D Transverse Optical Collimator

For the magnetic lens to achieve the desired results, the transverse velocities of the atoms entering the lens must be minimised. This can be achieved by the application of a 2-D transverse optical collimator [8]. This consists of multiple reflections of a resonant laser between two orthogonal sets of almost parallel mirrors. Two sets of counter-propagating, blue-detuned laser beams, one in each of the two dimensions, are used. The force acting on the atoms from these beams causes the atomic trajectories to be bent toward the beam axis until the transverse velocity is reduced almost to zero.

The slight angle of the mirrors causes the beam to strike the atoms at a decreasing angle after each reflection, thus accounting for Doppler shifting of the atoms from resonance.

#### **Zeeman Slower**

A spread in the longitudinal velocity of the atoms will result in an effect in the hexapole lens analogous to chromatic aberrations in an optical lens i.e. the focal length is velocity dependant. For a thermal neon beam ( $E_{kin}$  0.1eV) traversing our lens, this focal length is of the order of 10m. A result of this weak focussing is that atoms with large longitudinal velocities will be skimmed off and will not traverse the entire length of the bender.

To counter these problems we have implemented a Zeeman slower. This comprises a slightly red-detuned, longitudinally counter-propagating laser. As this beam slows the atoms, they are Doppler shifted from resonance and so a spatially varying solenoid is placed co-axial with the atomic beam. The atomic transition is then Zeeman shifted to maintain resonance with the laser. To accommodate this shift, the magnetic Zeeman field profile is defined as

$$B(z) = B_{bias} + B_0 \sqrt{1 - z/z_0}$$
 (4)

where  $B_{bias}$  is a constant bias field,  $B_0$  is the initial magnetic field and  $z_0$  is the length of the solenoid.

# **Experimental Apparatus**

A schematic of the experimental apparatus is depicted in Fig. 2. Atoms in a metastable state are generated through electron collision in a DC glow discharge. The atoms expand through the  $300\mu m$  boron nitride nozzle into the high vacuum source chamber. A discharge is generated between a cathode pin (-650 V) and the skimmer plate. As the atoms expand from the nozzle, electron collisions excite a fraction of the beam (0.01%) into the metastable state. A liquid nitrogen reservoir cools the atoms to around 77K.

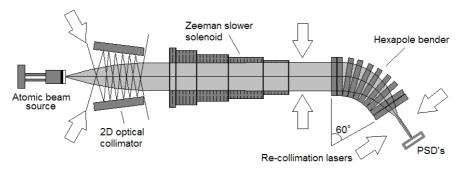


Figure 2. Schematic of the metastable neon beam

Time-of-flight experiments have determined the most probable longitudinal velocity of these atoms to be approximately  $620\text{ms}^{-1}$  with a FWHM spread of  $250\text{ms}^{-1}$ . The optimized metastable flux is  $3.4\times10^{14}\text{sr}^{-1}\text{s}^{-1}$ . The metastable neon atoms pass through the 2mm skimmer aperture into the collimator chamber. Here they are transversely cooled in two dimensions by the optical collimator. After optic fibre coupling to our experiment, the laser provides 640.404nm ( $^3P_2\rightarrow^3D_3$  cooling transition) light at approximately 25mW per 10mm diameter beam, which is around seven times the saturation intensity of the transition. The input and mirror angles of these beams are 100 and 2mrad respectively and the frequency of the laser is locked via a saturated absorption cell to a blue detuning of  $4\Gamma$ . This gives an effective detuning Doppler-shifted for a maximum atomic transverse velocity of  $50\text{ms}^{-1}$ .

The atomic beam then enters the Zeeman slower. The slowing laser beam is  $6\Gamma$  red detuned and is weakly focussing toward the source. The laser beam diameter and power are 20mm and 65mW respectively, resulting in around saturation power. The magnetic field parameters (B<sub>0</sub>=0.08T, B<sub>bias</sub>=0.04T, z<sub>0</sub>=920mm) and laser detuning are chosen to result in an exit velocity of  $40\text{ms}^{-1}$ .

After slowing, the atoms are recollimated by a 2D optical molasses. The atoms then pass through the hexapole bender arrangement. Each bender lens element consists of a circular arrangement of six NdFeB magnets (17×8.5×4.2mm), placed in a housing that maintains their position in the desired arrangement placed co-axial to the atomic beam. The inner radius of this arrangement is approximately 11mm and the magnetic field varies from 0T in the center to 0.4T over this distance. The magnetic remanence and permeability of the magnets are 1.2T and 1.08 respectively. The magnetic bender (Figure 1a) consists of ten hexapole lenses mounted on rails inside a curved tube vacuum chamber (axial radius of curvature 200mm) that constitutes a 60° bend. A second 2D optical molasses is then employed to recollimated the diverging atoms. The slowed, collimated atoms then enter the experiment chamber where position sensitive detectors (PSD's) are then used to determine the atomic beam spatial distribution and time-of-flight velocity characteristics.

# **Results**

Longitudinal time-of-flight measurements were conducted using a mechanical chopper apparatus for a range of laser detunings. Figure 3a shows the velocity distribution obtained for a laser red detuning of 300MHz and it is clear that a slowed atom distribution is present. The centre of the slowed distributions is around 330ms<sup>-1</sup>. Similar distributions were obtained for 350MHz, and 400MHz red detuned beams with centre velocities of 370ms<sup>-1</sup> and 390ms<sup>-1</sup> respectively. These detunings produce slowed atom distributions consistent with the simulated values of 290ms<sup>-1</sup>, 340ms<sup>-1</sup> and 390ms<sup>-1</sup> respectively. This verifies the accuracy of the MATLAB program written to simulate the atomic beam line. We can now establish that to

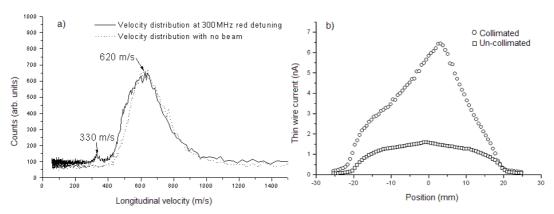


Figure 3. a) Longitudinal time-of flight results. b) Transverse spatial profiles for a collimated and un-collimated atomic beam at a distance of 98cm from the source.

produce the longitudinally slow beam required for the focusing system, the detuning must be brought closer to the resonant frequency. To obtain a longitudinal velocity group centred about  $40 \text{ms}^{-1}$ , a slowing laser beam possessing 50MHz red detuning, or  $\sim$  -6 $\Gamma$ , must be applied.

The transverse position profile of the beam was determined using a thin wire scanned across the beam before the hexapole lens (98cm from the source). The result of this scan is shown in Fig. 3b. It is observed that the FWHM of this distribution with the 2D collimator operating is substantially reduced. It is calculated that the beam density is increased approximately fourfold. By comparing this scan to another thin-wire scan taken immediately after the collimator (30cm from the source), we find the atomic beam divergence to be approximately 5mrad.

The magnetic field profile for a single hexapole lens element was obtained and shown in Fig.4a.

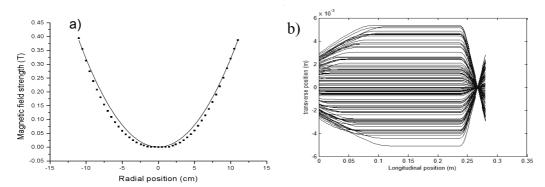


Figure 4 a) Graph of the magnetic field strength as a function of radial position in our hexapole lens (data points), compared to theoretical field profile (line). b) Monte-Carlo simulation of atom trajectories through the atom optical elements.

This shows good agreement with the theoretically required field and so the field gradient obtained from this graph was entered into the beam-modelling program. Figure 4b shows the atomic trajectories through this system. A focal length of 3cm is determined for these elements.

#### References

- [1] J. E. Lennard-Jones, Trans. Faraday Soc. 28, 334 (1932).
- [2] H.B.G. Casimir and D. Polder, *Phys. Rev.* **73**, 360 (1948).
- [3] F.Shimizu, Phys. Rev. Lett 86, 987 (2001).
- [4] H. Metcalf and P. van der Straten Laser Cooling and Trapping Springer, New York, (1999)
- [5] R.E. Grisenti, W. Schöllkopf, J.P. Toennies, G.C. Hegerfeldt and T. Köhler, Phys. Rev. Lett., 83 1755 (1999)
- [6] A. Anderson, S. Haroche, E.A. Hinds, W. Jhe and D. Meschede, Phys. Rev. A 37 3594 (1988)
- [7] C. Fabre and S. Haroche, *Rhydberg States of Atoms and Molecules*, edited by R.F. Stebbings and F.B. Dunning (Cambridge University Press) 1983.
- [8] M. D. Hoogerland, J. P. J. Driessen, E. J. D. Vredenbregt, H. J. L. Megens, M. P. Schuwer, H. C. W. Beijerink and K. A. H. van Leeuwen *Appl. Phys. B: Lasers Opt.* 62 323 (1996).